# Inverse Radiative Transfer Analysis for Ocean Optics

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## LONG-TERM GOALS

The long-term goal of this research is to support the work of ocean optics experimentalists by developing analytical and numerical methods for solving radiative transfer inverse problems. The research on inverse problems includes methods for the determination of

- the absorption and backscattering coefficients,
- the ocean bottom albedo,
- the ocean surface albedo, and
- the spatial dependence of sources (such as layers of bioluminescence)

from in-water natural-light measurements. A second long-term goal is to develop a new technique for designing an integrating cavity meter ICAM to measure the absorption coefficient.

## OBJECTIVES

The short-term objectives of the work on solving inverse problems were to test with experimental data a method for determining the absorption and backscattering coefficients from natural-light measurements and to develop and numerically test methods for the determination of

- the absorption and backscattering coefficients with a more general approach,
- the bottom albedo,
- the sea surface albedo, and
- the spatial dependence of sources (such as layers of bioluminescence)

from in-water natural-light measurements. The short-term objective of the work on solving forward problems was to analyze in general geometry

- the design of an ICAM either in a closed-chamber or a flow-through configuration.

## APPROACH

The radiative transfer equation is the basis for most of the development and numerical testing of analytical inverse methods. These methods, because they are derived directly from the radiative transfer equation, require little or no iteration and therefore are especially useful for processing large amounts of data. The work on the determination of the absorption and backscattering coefficients is being continued with Robert Leathers of the Office of Naval Research. He is examining a generalized approach to the results reported in Ref. 1, a report coauthored with Collin Roesler of Bigelow Laboratories.

A "chord method" is used for the analysis of an integrating cavity for the measurement of the absorption coefficient of pure water with the ICAM constructed by Ed Fry and co-workers (Refs. 2 and 3) The chord method generalizes the spherical cavity analysis by John Kirk (Ref. 4). Richard Sanchez of the Commisariat d'Energie Atomique also is assisting in the investigation of a method for correcting this approach for single scattering events.

# Report Documentation Page

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## WORK COMPLETED

### Inverse Problem Analyses

• *Inherent Optical Property Determination.* An algorithm for estimating the absorption coefficient $a$ and the backscattering coefficient $b_b$ from measurements of the upward and downward irradiances $E_u(z)$ and $E_d(z)$ or from $L_u(z)$ and $E_d(z)$ has been published (Ref. 1). With this method, for example, the reflectance ratio $R(z)$ and the downward diffuse attenuation coefficient $K_d(z)$ were obtained from $E_u(z)$ and $E_d(z)$, and the values of the inherent optical properties $R_\infty$ and $K_\infty$ were estimated from $R(z)$ and $K_d(z)$, respectively. For an assumed scattering phase function there are unique correlations between the values of $R_\infty$ and $K_\infty$ and those of $a$ and $b_b$ that can be derived from the radiative transfer equation. A similar approach was used with $E_u(z)$ replaced by $L_u(z)$.

• *Bottom Albedo Determination.* Two reflectance models were developed to estimate the albedo of the sea bottom in optically shallow waters. Either measurements of the downward and upward irradiances or the normally directed upward radiance and the downward irradiance are required. Numerical testing with solutions of the forward problem were used to test the efficacy of the algorithms and to compare their performance to other algorithms in the literature. This work was revised and published in Ref. 5.

### Integrating Cavity Absorption Meter Analyses

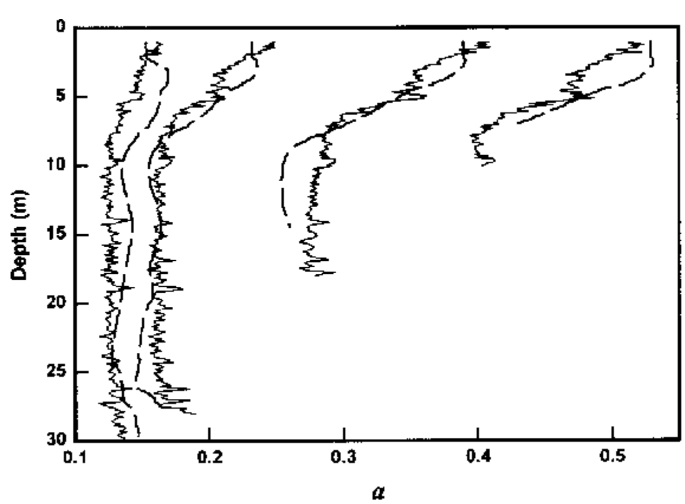
We have generalized the analysis for the design of closed-chamber integrating cavity absorption meters to account for the probability of photon survival in general geometries. Numerical calculations in Ref. 6 illustrate the effect of non-spherical geometries on the estimated absorption coefficient. A preliminary analysis (Ref. 7) also has been published of the equations necessary to design a flow-through ICAM.

## RESULTS

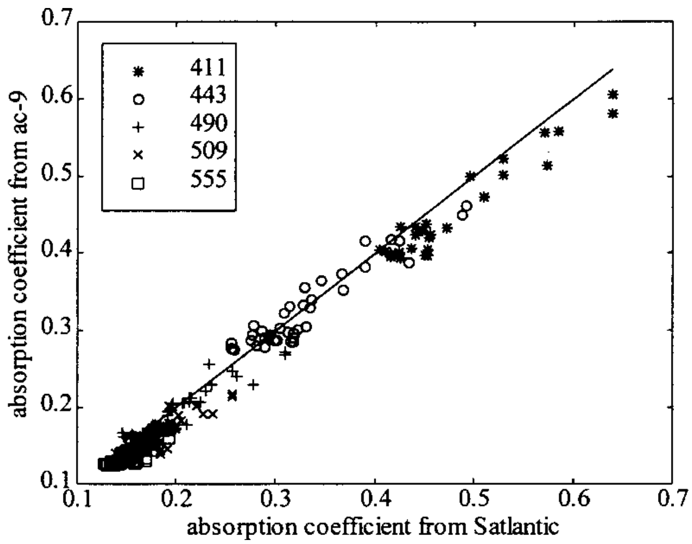
### Inverse Problem Analyses

• *Inherent Optical Property Determination.* The inverse algorithm equations were tested with numerically simulated data as well as with measurements taken in Long Island Sound. A Satlantic Upwelling Radiance Sensor OCR-200 was used to obtain $L_u(z)$ and a Satlantic Downwelling Irradiance Sensor OCI-200 was flipped vertically between casts to obtain alternatively $E_u(z)$ and $E_d(z)$. Profiles of $a(z)$ obtained from the Satlantic measurements with the use of the algorithms were compared with those obtained with a WetLabs ac-9 instrument. Comparisons of the $L_u(z)$-$E_d(z)$ method are shown in Figs. 1 and 2 from Ref. 1, with comparable results for the $E_u(z)$-$E_d(z)$ method.

***1. Comparison at one site of estimates of the absorption coefficients at (from left to right) 555, 490, 443, and 411 nm from the ac-9 (solid curve) with those from the $L_u(z)$-$E_d(z)$ method (dashed curve).***



***2. Absorption coefficients determined with the $L_u(z)$-$E_d(z)$ method versus those obtained with the ac-9. Included are data at 2-m intervals from seven sites and five wavelengths from 411 to 555 nm.***




In general, good estimates of $a$ and $b_b$ were obtained from $R_\infty$ and $K_\infty$ when the assumed scattering phase function was approximately correct. It is important to use a realistic scattering phase model (e.g., a Petzold phase function) in the inverse solution because $b_b$ is sensitive to the backscattering portion of the phase function. The method works best in deep homogeneous waters.

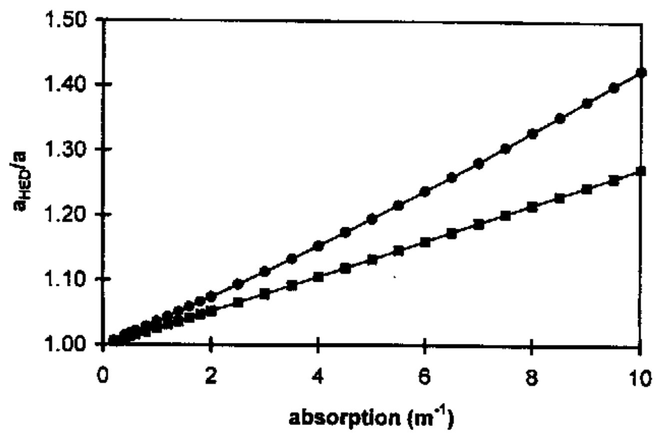
This work is being continued with Robert Leathers using a generalized algorithm that accounts for stratified variations of the optical properties to see if discontinuities in the absorption and backscattering coefficients can be discerned.

• *Bottom Albedo Determination.* The new method developed here (Ref. 5) requires measurements from only one site whereas a previously published method requires additional measurements at a nearby deep-water site in order to provide a reference base for the measurements at the desired site. Both the new and old methods can utilize mesurements away from the sea bottom to avoid self-shielding errors.

**Integrating Cavity Absorption Meter Analyses**

The performance of a cylindrically shaped cavity is easily analyzed with the new equation for the survival probability of photons uniformly and isotropically illuminating the cavity. The error in the use of an assumption that the energy density is homogeneous can now be assessed for existing meters rather than for those of only a spherical shape. Figure 3 (Ref. 6) shows there is a difference between use of a "homogeneous energy density" (HED) assumption for a spherical design and the cylindrical design more typical of the construction of actual instruments.

***3. Ratio of absorption coefficient from the homogeneous-energy-assumption to the true absorption coefficient, $a_{HED}/a$, versus the true coefficient in inverse meters. The lower curve is for a cylinder with dimensions of the Fry et al. ICAM and the upper curve is for a sphere of equal volume.***




## IMPACT/APPLICATIONS

Determination of inherent optical properties is a primary goal of optical oceanographers for use in environmental monitoring. Inversion of the light field to determine inherent optical properties from apparent optical properties has direct application to in-water and remote sensing of ocean color. Since the chlorophyll concentration cannot be used to correlate the optical properties for coastal waters, the inversion is more difficult for such waters than for open ocean waters. The analytically-based algorithms developed here will help in this inversion process and in obtaining optical closure.

The analysis for an integrating cavity absorption meter of general geometry will be important for the future design of meters used to measure waters with relatively large absorption coefficients.

## TRANSITIONS

The efficacy of our approach for the determination of $a$ and $b_b$ from either $E_u(z)$ and $E_d(z)$ or the vertically upward radiance $L_u(z)$ and $E_d(z)$ was published in Ref. 1 for experimental data collected from stations in Long Island Sound. The approach also will be used by Robert Leathers at the Naval Research Laboratory for additional experimental data.

## RELATED PROJECTS

Curtis Mobley of Sequoia Scientific Inc. and I prepared a list of definitions in the field of optical oceanography for use by people entering the field and by students, e.g., those in summer courses such as the Ocean Optics Summer Courses at Friday Harbor Laboratories in 1995 and 1998. The definitions are to be published (Ref. 8), but permission has been granted by the publisher to permanently retain the definitions at the website http://www.me.washington.edu/faculty/McCormick.

I am working with a post-doctoral student, Ayse Kaskas, who is supported by the Scientific and Technical Research Council of Turkey, to see if additional in-water, natural light irradiance measurements, besides downward and upward irradiance measurements, might be useful when inferring inherent optical properties. The idea is to also orient the face of the detector vertically rather than horizontally. This work possibly could lead to an extension of the method employed in Ref. 1.

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